ULTRA-PERIPHERAL PHYSICS AT FORWARD ANGLES

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RHIC-II Forward & p-A Physics

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I.MUTUAL COULOMB DISSOCIATION

II.COHERENT VECTOR MESON PRODUCTION

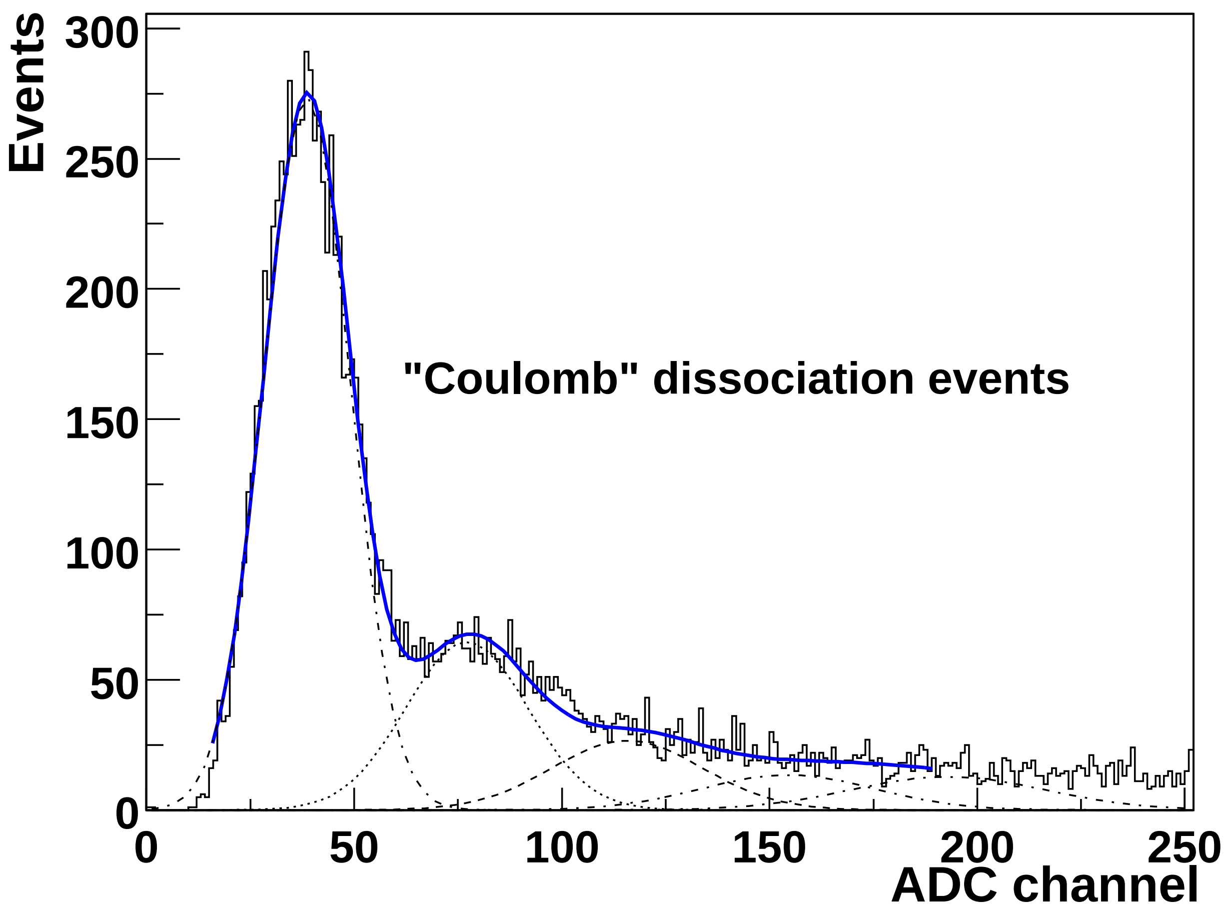
III. CALCULATION OF HEAVY ION e^+e^- PAIR PRODUCTION TO ALL ORDERS IN $Z\alpha$

A.J.B., Phys. Rev. C 71, 024901 (2005)

I. MUTUAL COULOMB DISSOCIATION

- Measurement of mutual Coulomb dissociation was found to be in good agreement with earlier theoretical calculations.

M. Chiu et al., Phys.Rev.Lett. 89, 012302 (2002)



$\sigma_{\mathbf{i}}$	**PHENIX**	**PHOBOS**	**BRAHMS**	**[1]**	**[2]**
σ_{tot}	–	–	–	10.8 ± 0.5	11.2
σ_{geom}	–	–	–	7.1	7.3
$\frac{\sigma_{geom}}{\sigma_{tot}}$	$.661 \pm .014$	$.658 \pm .028$	$.68 \pm .06$	.67	.659
$\frac{\sigma(1,X)}{\sigma_{tot}}$	$.117 \pm .004$	$.123 \pm .011$	$.121 \pm .009$	.125	.139
$\frac{\sigma(1,1)}{\sigma(1,X)}$	$.345 \pm .012$	$.341 \pm .015$	$.36 \pm .02$	.329	–
$\frac{\sigma(2,X)}{\sigma(1,X)}$	$.345 \pm .014$	$.337 \pm .015$	$.35 \pm .03$	–	.327
$\frac{\sigma(1,1)}{\sigma_{tot}}$	$.040 \pm .002$	$.042 \pm .003$	$.044 \pm .004$	$.041 \pm .002$	-

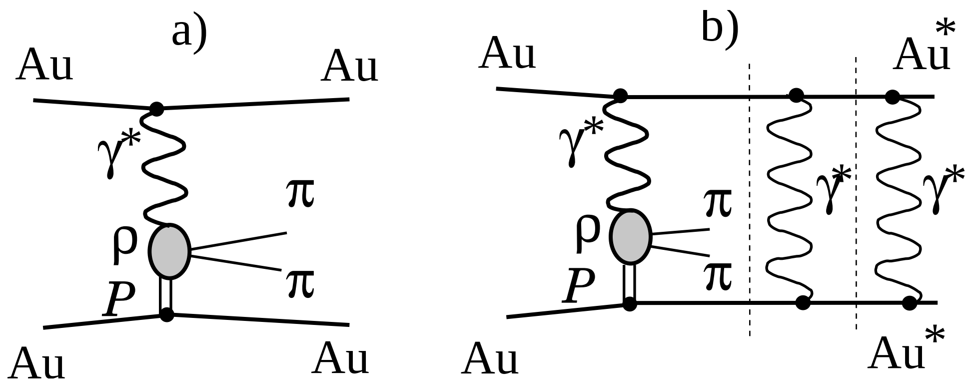
[1] A. J. B., C. Chasman, and S. White, Nucl. Instr. and Meth. A415, 1 (1998)

[2] I. A. Pshenichnov, et al., Phys. Rev. C 64, 024903 (2001)

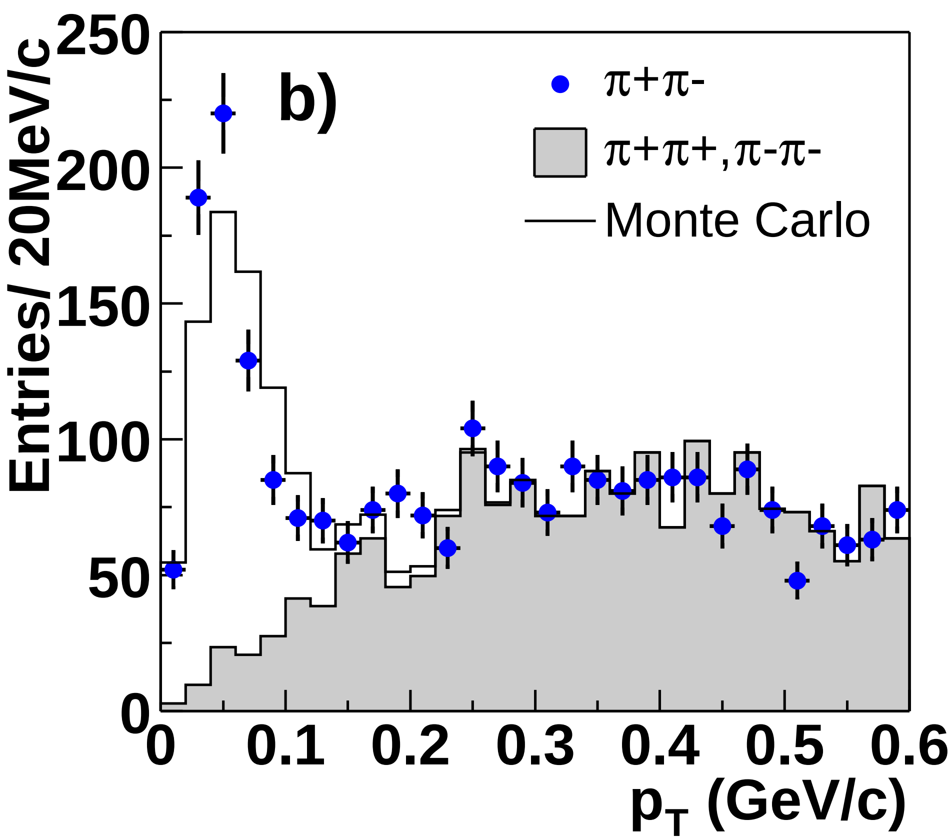
- Ratios of cross sections for experiment and theory. The values of σ_{tot} and σ_{geom} are in barns.

II. COHERENT VECTOR MESON PRODUCTION

C. Adler et al., Phys.Rev.Lett. 89, 272302 (2002)



- The photon fluctuates into a ρ and is knocked on-shell by scattering on the nucleus.



- The ρ signal is from oppositely charged pions.

Cross Section	STAR (mb)	[*] (mb)
$\sigma^{\rho}_{xn,xn}$	$28.3 \pm 2.0 \pm 6.3$	27
$\sigma^{\rho}_{1n,1n}$	$2.8 \pm 0.5 \pm 0.7$	2.6
$\sigma^{\rho(\text{inc.overlap})}_{xn,xn}$	$39.7 \pm 2.8 \pm 9.7$	–
$\sigma^{\rho}_{xn,0n}$	$95 \pm 60 \pm 25$	–
$\sigma^{\rho}_{0n,0n}$	$370 \pm 170 \pm 80$	–
σ^{ρ}_{total}	$460 \pm 220 \pm 110$	350

[*] A. J. B., S. R. Klein, and J. Nystrand, Phys.Rev.Lett. 89, 012301 (2002)

- Observed ρ production rates are compared to predictions[*]. The uncertainties are highly correlated.

Meson	Au+Au, RHIC	Pb+Pb, LHC
	σ [mb]	σ [mb]
ρ^0	590	5200
ω	59	490
ϕ	39	460
J/Ψ	0.29	32

- Predicted cross sections for exclusive vector meson production in Au+Au and Pb+Pb interactions at RHIC and the LHC, respectively[*].

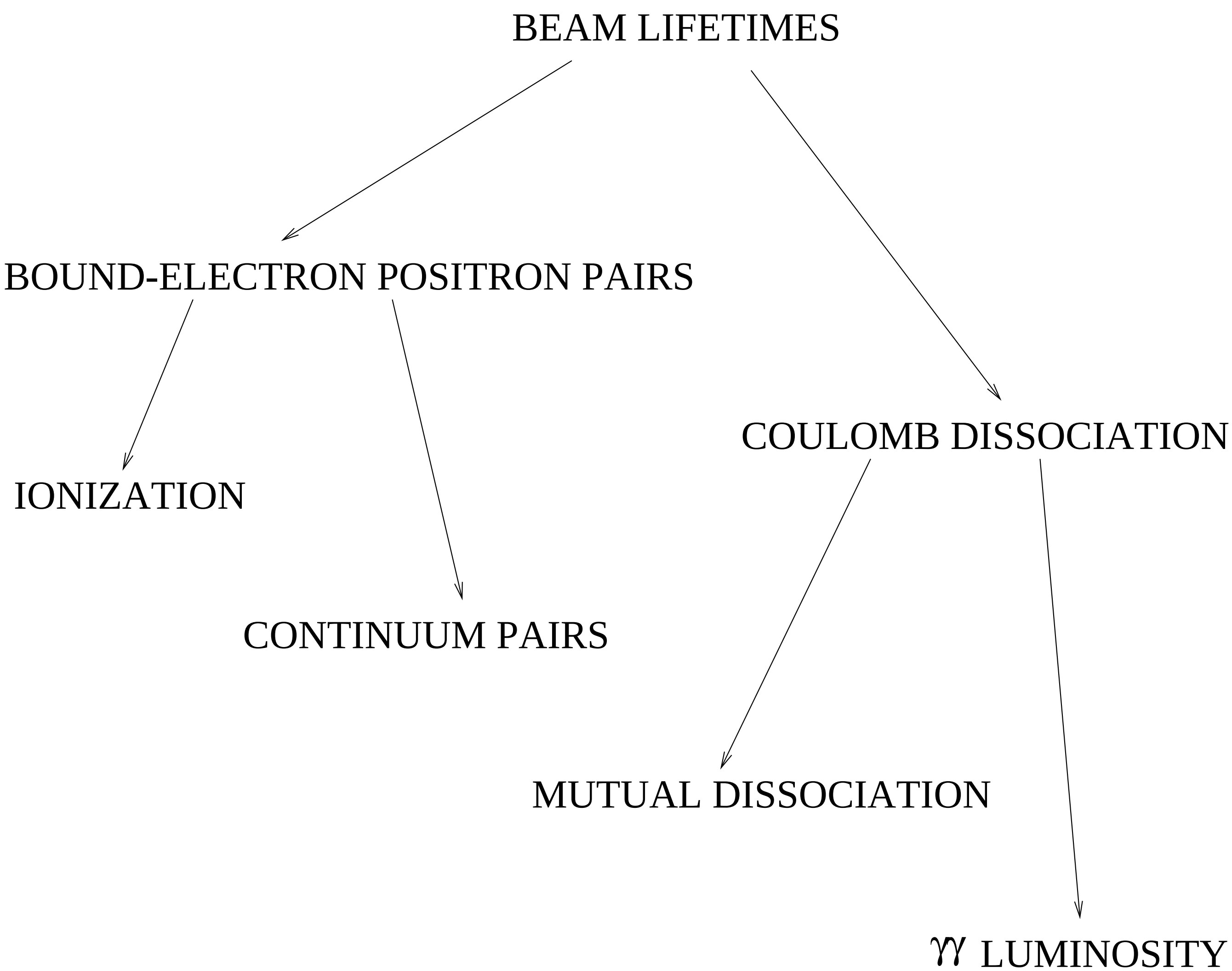
  [*]Spencer R. Klein and Joakim Nystrand, Phys. Rev. C 60, 014903 (1999)

- J/Ψ production is predicted to be a factor of 2000 down from ρ production at RHIC.

- Can RHIC2 make coherent J/Ψ production feasable?

III. CALCULATION OF HEAVY ION e^+e^- PAIR PRODUCTION TO ALL ORDERS IN $Z\alpha$

A.J.B., Phys. Rev. C 71, 024901 (2005)



Summary:

- Heavy ion total cross sections for e^+e^- pair production at RHIC, SPS, and LHC have been calculated to all orders in $Z\alpha$;

Technique:

- Delta function longitudinal potential combined with an eikonalized tranverse potential for higher order $Z\alpha$;
- The same energy dependent cutoff of the potential as that conventionally used in numerical perturbation theory calculations.
- Numerical evaluation of cross sections on a computer.

Result:

- The "exact" calculation of heavy-ion e+e- pair production gives a total cross section reduced from the perturbation theory result.

CONTINUUM PAIRS

- Two center light cone calculation of continuum pairs by solving the semi-classical Dirac equation for colliding δ function potentials

$$V(\boldsymbol{\rho}, z, t) = \delta(z-t)(1-\alpha_z)\Lambda^-(\boldsymbol{\rho}) + \delta(z+t)(1+\alpha_z)\Lambda^+(\boldsymbol{\rho})$$

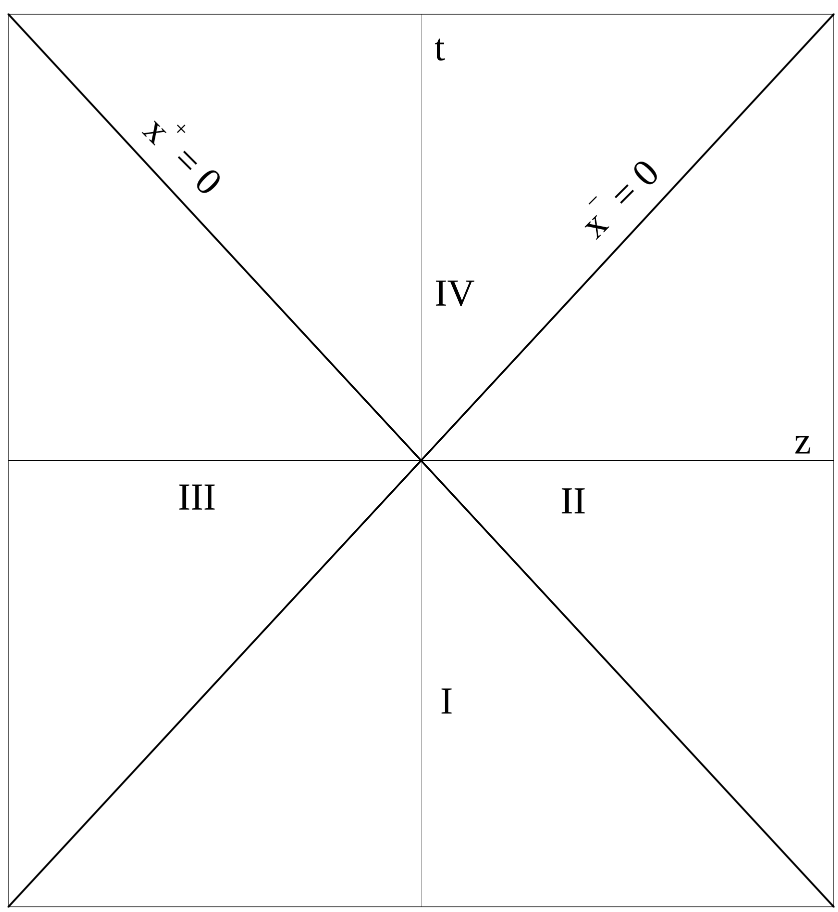
in collider center of mass (lab) frame, and

$$\Lambda^{\pm}(\boldsymbol{\rho}) = -Z\alpha \ln \frac{(\boldsymbol{\rho} \pm \mathbf{b}/2)^2}{(b/2)^2}$$

B. Segev and J. C. Wells, Phys. Rev. A 57, 1849 (1998)

A.J.B., Larry McLerran, Phys. Rev. C 58, 1679 (1998)

U. Eichmann, J. Reinhardt, S. Schramm, and W. Greiner, Phys. Rev. a 59, 1223 (1999)



- A.J.B. and McLerran noted the agreement of their result with perturbation theory even for large Z.

- Segev and Wells also note the agreement with perturbation theory and note the scaling with $Z_1^2 Z_2^2$ seen in SPS data.

  B. Segev and J. C. Wells, Phys. Rev. C 59, 2753 (1999)

- CERN SPS data

  160 GeV/c Pb ions on C, Al, Pa, Au; 200 Gev/c S ions on C, Al, Pa, Au: "Cross sections scale as the product of the squares of the projectile and target nuclear charges"

  C. R. Vane, S. Datz, E. F. Deveney, P. F. Dittner, H. F. Krause, R. Schuch, H. Gao, and R. Hutton, Phys. Rev. A 56, 3682 (1997)

- On the other hand, photoproduction on a heavy target shows a negative correction proportional to Z^2.

  H. A. Bethe and L. C. Maximon, Phys. Rev. 93, 768 (1954); Handel Davies, H. A. Bethe and L. C. Maximon, Phys. Rev. 93, 788 (1954)

- Several authors have argued that a correct regularization of the exact Dirac equation amplitude should lead to Coulomb corrections.

  D. Yu. Ivanov, A. Schiller, and V. G. Serbo, Phys. Lett. B 454, 155 (1999)

  R. N. Lee and A. I. Milstein, Phys. Rev. A 61, 032103; 64, 032106

HIGHER ORDER COULOMB CORRECTIONS

- Lee and Milstein calculated higher order Coulomb corrections to pertubation theory analytically, based on the exact Dirac equation solution.

- I have previously tried to explicate the Lee and Milstein approximate results and argued their qualitative correctness.

  A.J.B., Phys. Rev. C 68, 034906 (2003)

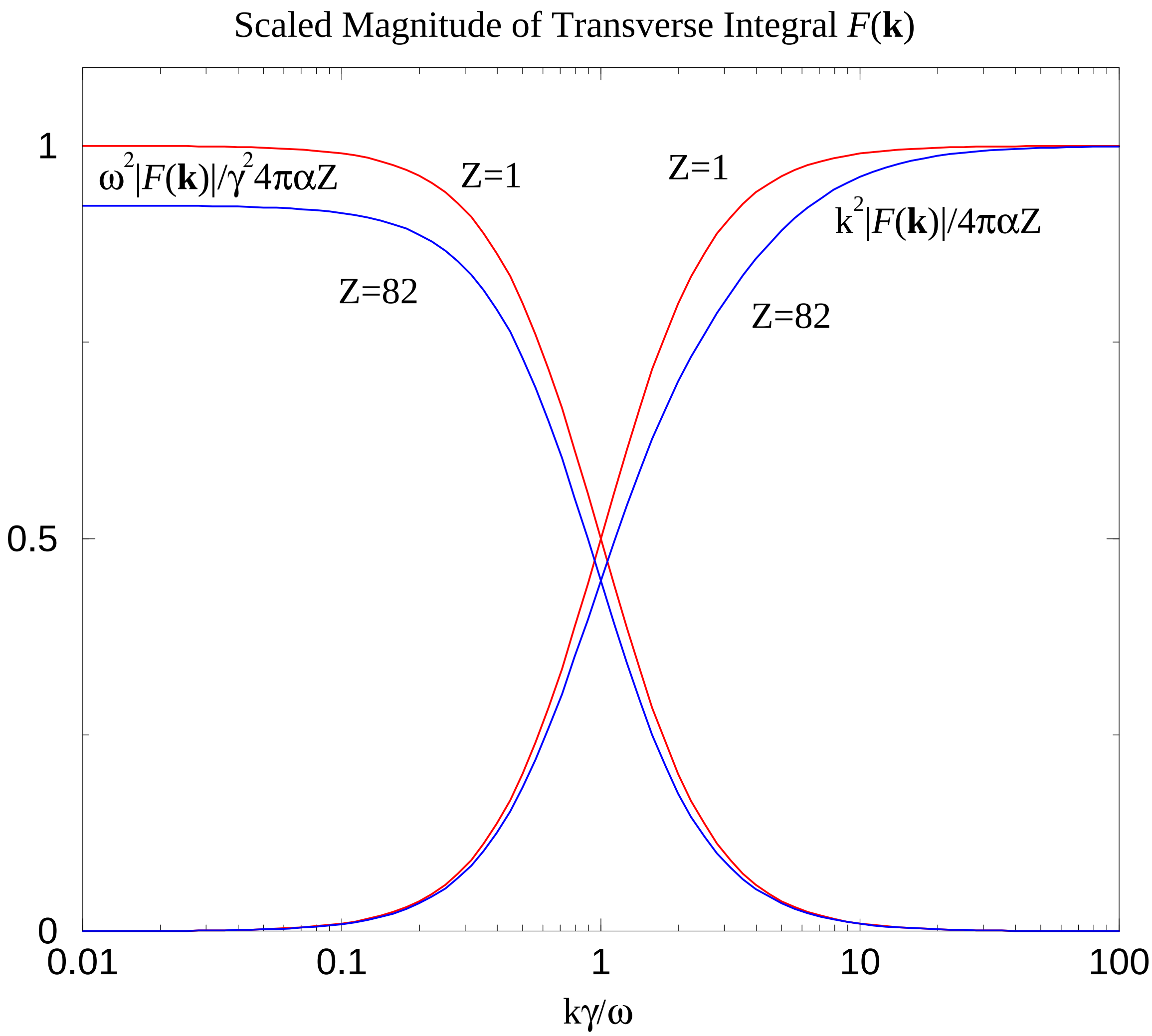
- Here I present a numerical evaluation of the "exact" Dirac equation cross sections on a computer.

- My strategy is to apply a physical cutoff to the transverse potential (which had been set to $2Z\alpha \ln \rho$) that leads to known perturbation theory results in that limit.

- Instead of regularizing the transverse integral itself and letting the cutoff radius go to infinity as was originally done I apply an appropriate physical cutoff to the interaction potential.

- The modified Bessel function $K_0(\rho\omega/\gamma) = -\ln(\rho\omega/2\gamma)$ for small ρ and cuts off exponentially at $\rho \sim \gamma/\omega$. This is the physical cutoff to the transverse potential.

Coulomb Corrections



Results of numerical calculation of the scaled magnitude of $F(\mathbf{k})$ as a function of $k\gamma/\omega$ for $Z = 1$ (essentially perturbative) and for $Z = 82$.

$F(\mathbf{k})$ goes to $4\pi\gamma^2/\omega^2$ as k goes to zero in the $Z = 1$ perturbative case;

$F(\mathbf{k})$ goes to a reduced constant value as k goes to zero for $Z = 82$.

CALCULATIONS: NUMERICAL TECHNIQUES AND RESULTS

- The expression for the total cross section involves an eight dimensional integral over the positron and electron momenta as well as the virtual photon transverse momentum.

- Reduces to seven dimensions in the usual way by symmetry, e. g. let the positron transverse momentum define the x-axis.

- The usual method of evaluation e. g. in perturbation theory is via Monte Carlo.

- I have chosen to do the seven dimensional integral directly on meshes uniform on a logarithmic scale in each momentum dimension.

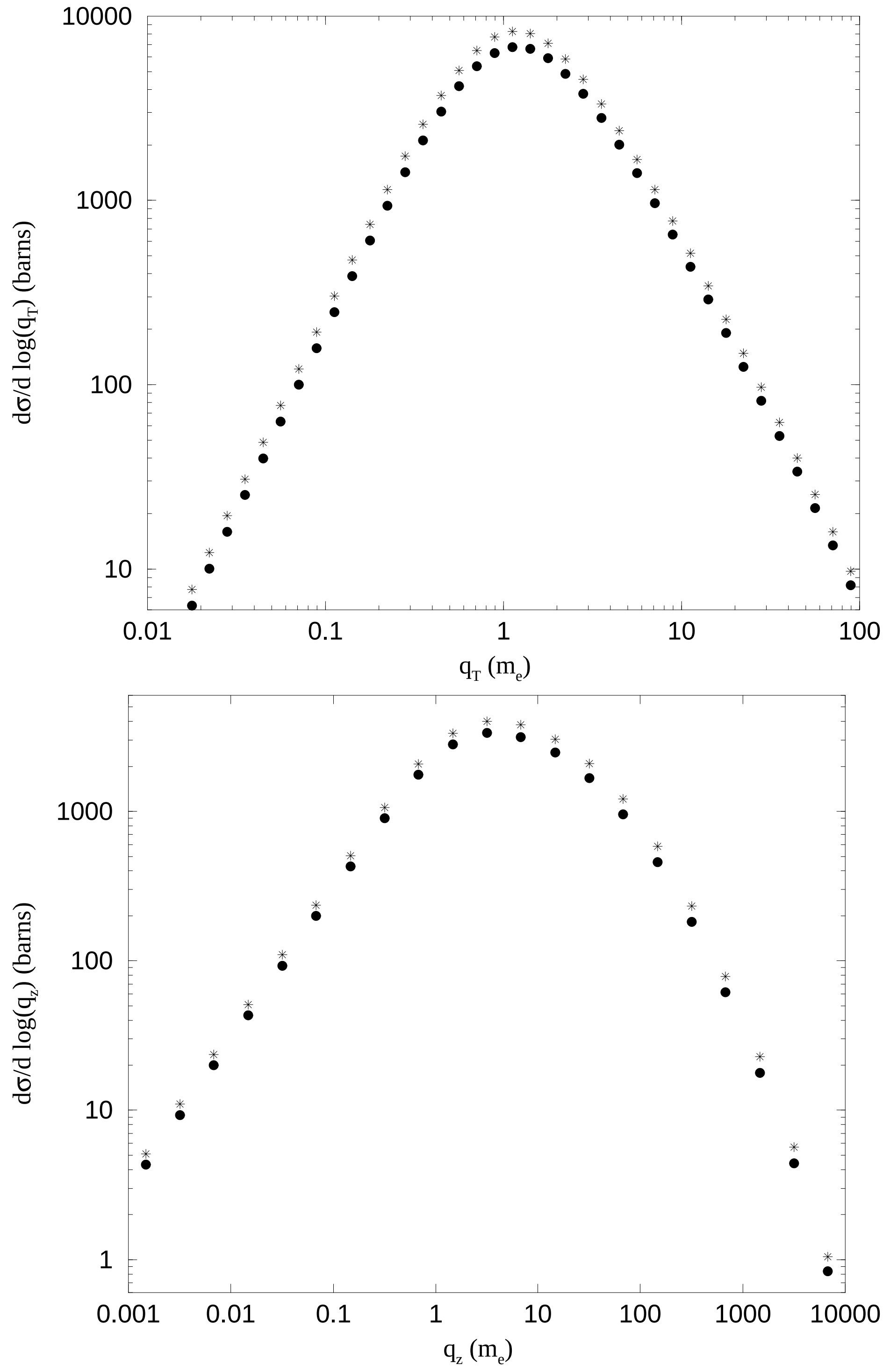
- It was possible to carry the calculation out without using Monte Carlo because the integrand is very smooth and smoothly goes to zero at both high end and low end of the momentum ranges.

- No cutoffs were applied except the cutoffs implicit in the $\omega_{A,B}/\gamma$ of the of the virtual photon sources $F_{A,B}(\mathbf{k})$.

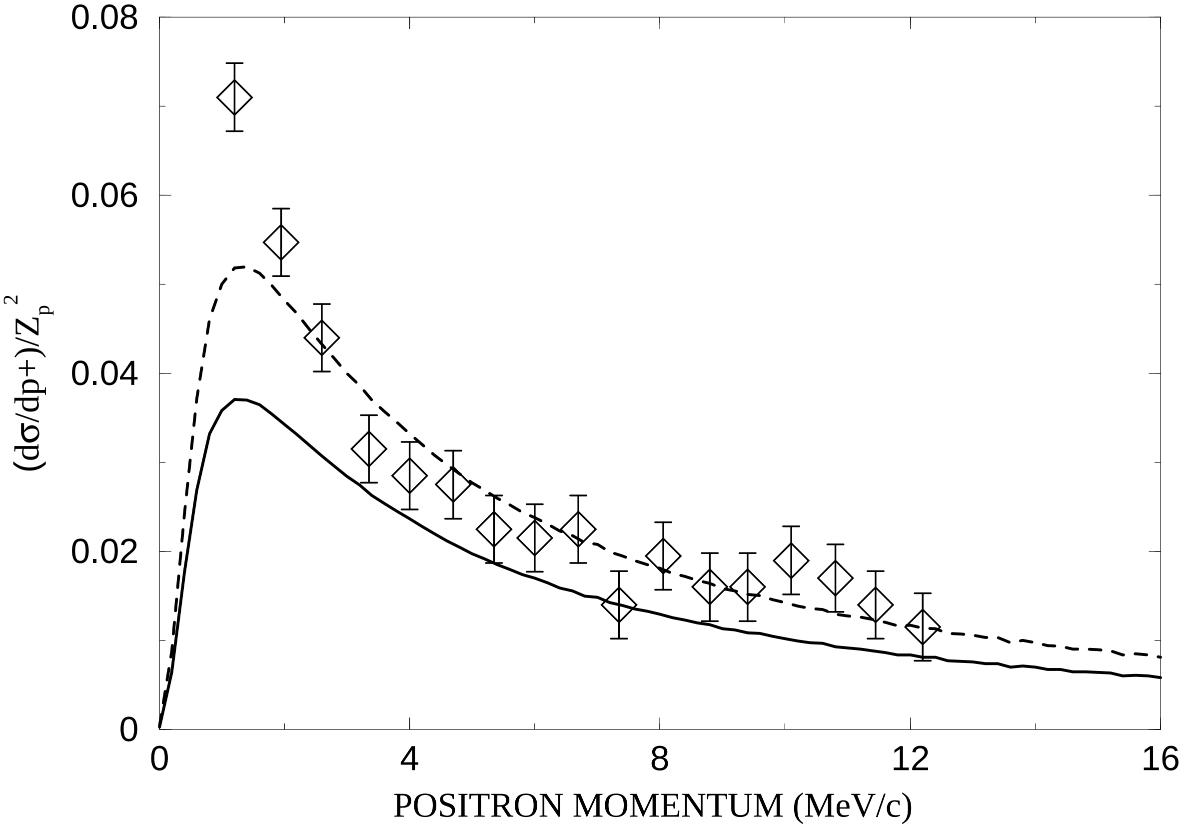
	Results in barns	Exact	Perturb.	Difference
Pb + Au	Computer Evaluation	2670	3720	-1050
$\gamma = 9.2$	Racah Formula		3480	
SPS	Lee-Milstein	3050	5120	-2070
Au + Au	Computer Evaluation	28,600	34,600	-6,000
$\gamma = 100$	Racah Formula		34,200	
RHIC	Lee-Milstein	34,100	42,500	-8,400
	Hencken, Trautman, Baur		34,000	
Pb + Pb	Computer Evaluation	199,000	224,000	-25,000
$\gamma = 2960$	Racah Formula		226,000	
LHC	Lee-Milstein	226,000	258,000	-32,000

Kai Hencken, Dirk Trautmann, and Gerhard Baur, Phys. Rev. C 59, 841 (1999)

- The perturbative computer calculations are in fair agreement with the Racah formula as expected.
- The Lee-Milstein higher order correction to the Landau-Lifshits formula is negative but somewhat larger than that evaluated here numerically.

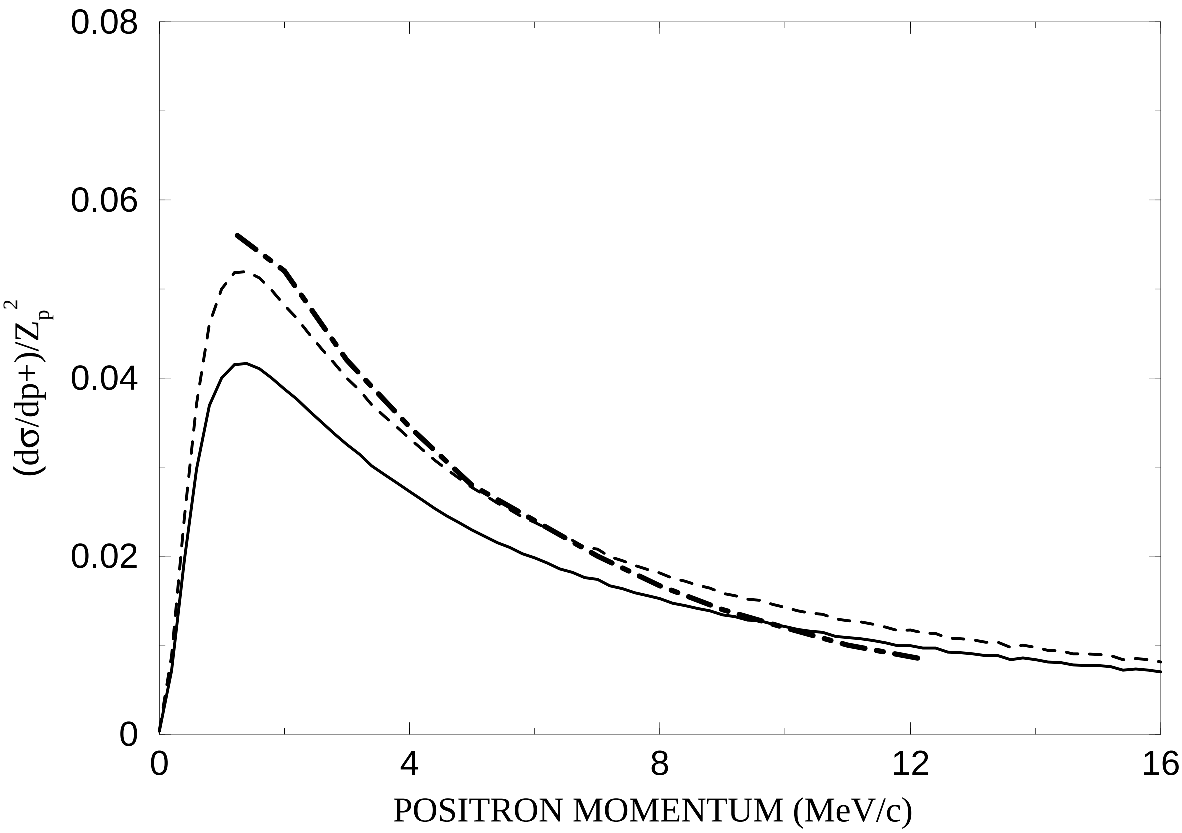


- Positron transverse (above) and longitudinal (below) momentum spectra for Au + Au at RHIC with $\gamma = 100$. The exact calculations (filled circles) are below perturbation theory (stars) for the entire range of $\mathbf{q}_\perp$ and q_z.



- Calculated positron momentum spectra compared with the CERN SPS data for Pb + Au. The solid line is the exact calculation and the dashed line perturbation theory.

C. R. Vane, S. Datz, E. F. Deveney, P. F. Dittner, H. F. Krause, R. Schuch, H. Gao, and R. Hutton, Phys. Rev. A 56, 3682 (1997)



- Calculated positron momentum spectra compared with the CERN SPS data for S + Au. The dot-dashed line follows the experimental authors' repesentation of their data. The solid line is the exact calculation and the dashed line perturbation theory.

C. R. Vane, S. Datz, E. F. Deveney, P. F. Dittner, H. F. Krause, R. Schuch, H. Gao, and R. Hutton, Phys. Rev. A 56, 3682 (1997)

STAR DATA

- The first experimental observation of e^+e^- pairs at RHIC has been published by STAR

  STAR Collaboration, J. Adams *et al.*, Phys. Rev. C **70**, 031902(R) (2004)

- Events were recorded where pairs were accompanied by nuclear dissociation. Comparison with perturbative QED calculations allowed a limit to be set "on higher-order corrections to the cross section,

$$-0.5\sigma_{QED} < \Delta\sigma < 0.2\sigma_{QED}$$

  at a 90% confidence level."

- A comparison of calculations in the STAR acceptance without dissociation is of interest as an indication of the relative difference between perturbation theory and the regularized exact result. In the STAR acceptance the exact result is calculated to be 17% lower than perturbation theory. Thus this rough estimate gives

$$\Delta\sigma = -0.17\sigma_{QED}$$

  and is not excluded by STAR.

FORWARD PAIRS AT LHC

- A sample numerical calculation has been performed using the same method for e^+e^- production by Pb + Pb ions with cuts from a possible detector setup at LHC. With electron and positron energy E and angle θ in the range,

$$3 \text{ Gev} < \text{E} < 20 \text{ GeV}$$

and

$$.00223 \text{ radians} < \theta < .00817 \text{ radians},$$

the no form factor perturbation theory cross section of 2.88 b is reduced by 18% to 2.36 b in an exact numerical calculation.

- If forward e^+e^- pairs are to be employed for luminosity measurements at LHC, then it seems necessary to consider the Coulomb corrections to the predicted cross sections.

e^+e^- PAIRS CONCLUSIONS

- A full numerical evaluation of the "exact" semi-classical total cross section for e^+e^- production with gold or lead ions shows reductions from perturbation theory of 28% (SPS), 17% (RHIC), and 11%(LHC).

- For large Z no final momentum region was found in which there was no reduction or an insignificant reduction of the exact cross section from the perturbative cross section.

- The CERN SPS data cover a large part of the momentum range of produced positrons, and there is a predicted reduction of cross section at high Z from the perturbative result. Perhaps the solution to the puzzle is that quality of the data is insufficient support perturbative $(Z_A^2 Z_B^2)$ scaling.

POSSIBLE CONSIDERATIONS FOR RHIC2

- Will RHIC2 improvements make observation of coherent J/Ψ production possible?
- The predicted reduction of continuum e^+e^- pair production from $Z_A^2 Z_B^2$ scaling at higher Z has never been observed experimentally.
  Can electromagnetic e^+e^- pair production be compared in Au + Au with e.g. Ca + Ca at RHIC2?